MEASUREMENT OF PARTICULATE MATTER EMISSIONS FROM CORN RECEIVING OPERATIONS WITH SIMULATED HOPPER–BOTTOM TRUCKS

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ABSTRACT. *Dust emissions from grain elevator operations can be a safety and health risk as well as a nuisance. Fundamental data on air entrainment and dust emission are needed for designing adequate and effective dust emission control methods. This study measured the amount of entrained air and emitted dust during corn receiving operations at an elevator operated by the USDA–ARS Grain Marketing and Production Research Center in Manhattan, Kansas. Shelled corn (maize) was unloaded from a storage bin, representing a hopper–bottom truck, to the receiving pit at rates of 17 to 262 kg/s and drop heights of 38 to 56 cm. Airflow rates were measured with propeller anemometers. The emission rates of total suspended particulates (TSP) and particulate matter smaller than 10 μm aerodynamic diameter (PM10) were measured with high–volume particulate samplers. The amount of air entrained per unit volume of grain decreased with increasing grain flow rate (0.26 to 2.07 m³/m³). The emission rates of TSP (8.3 to 52.1 g/metric ton of grain received) and PM10 (0.6 to 6.1 g/t) decreased with increasing grain flow rate and decreasing drop height.*

Keywords. Dust control, Grain dust, PM10, TSP.

G rain kernels have the potential of emitting particulates because of their inherent dustiness and the dirt that is mixed with the grain during harvesting and transport (Wallace, 2000). In addition, dust is generated by the abrasion and attrition of grain kernels whenever the grain mass is mechanically transferred or conveyed. Dust emitted during grain handling is composed approximately of 70% organic material, 17% free silica (silicon dioxide), and other materials, which may include particles of grain kernels, spores of smuts and molds, insect debris, pollens, and field dust (Health and Hygiene, Inc., as cited in Midwest Research Institute, 1998). The dust generated may affect the health of workers, cause air pollution, and contribute to dust explosions.

One of the most critical areas for controlling grain dust is the receiving area, where trucks and railcars are unloaded. Grain receiving generates dust–laden air as grain is dumped from a truck or car and falls into the receiving pit. Dust–laden air results from the displacement of air from the pit and the aspiration or entrainment of air caused by falling grain (Midwest Research Institute, 1998). The amount of dust emitted during receiving operations depends on grain flow rate, drop height, type of grain, quality or grade of grain, moisture content of the grain, degree of enclosure in the receiving area, and effectiveness of dust capture/collection systems. Preventive measures including use of doors or baffles in the receiving area and reduction of grain free–fall distance and grain velocities by choke unloading can minimize emissions. Additionally, many grain facilities, except for relatively small grain elevators, use dust capture/collection systems on the receiving pits to reduce dust emission to acceptable levels (Wallace, 2000). These dust capture/collection systems should be designed to extract a volume of air that matches the air entrained and the volume displaced by the grain mass. Previous studies on air entrainment have concentrated on powders and other bulk materials (Hemeon, 1963; Dennis and Bubenick, 1983; Plinke et al., 1995; Cooper and Arnold, 1995). Limited research has been conducted on the air entrainment during grain receiving operations.

Some information is available on dust emissions from grain handling and processing facilities; however, data on the particle size distribution of these emissions and on the fraction of emissions that might be a health hazard are limited (Wallace, 2000). Most of the information on particle size distribution was based on dust collected from baghouse and cyclone discharge and not directly from grain handling operations such as grain receiving (Martin and Sauer, 1976; Martin, 1981; Lai et al., 1984). Kenkel and Noyes (1995) measured the amount of grain dust generated when receiving wheat at a country elevator; receiving grain from a straight truck emitted 19.4 g/t of airborne dust, while receiving grain from a hopper–bottom truck emitted 9.5 g/t. Shaw et al. (1998) measured a mean dust emission rate of 8.5 g/t for corn

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receiving operations at three feed mills in cattle feed yards. Midwest Research Institute (1998) also conducted emission tests in grain receiving and shipping operations in both country and terminal elevators; mean dust emission rates were 150 g/t for straight truck receiving and 16 g/t for hopper truck receiving.

Emission factors have also been established for grain elevators in terms of total suspended particulates (TSP) and particulate matter less than 10 μm in aerodynamic diameter (PM10). PM10 is the fraction of the TSP that penetrates to the thorax or chest region (Hinds, 1999). It can accumulate in the respiratory system and is associated with several health problems such as asthma, increased respiratory symptoms, and decreased lung function (EPA, 1997). Concentrations of suspended particulates above the minimum explosive concentrations (MEC) also increase the risk of dust explosions. Fine particulates such as PM10 are more dangerous in terms of dust explosions, as MEC generally decreases with decreasing particle size (Garret et al., 1982). Emission factors are rated based on the reliability of the emission source, sampling procedure, and analysis of the test data. For grain elevators, emission factors were given the lowest rating possible (rating of E) (EPA, 1998).

More research is needed to quantify air entrainment and dust emission rates in grain elevators. This study was conducted to determine the amount of entrained air as affected by grain flow rate and the emission rates of TSP and PM10 as affected by grain flow rate and drop height during corn receiving operations involving simulated hopper–bottom trucks.

METHODOLOGY

All experiments were conducted at an elevator operated by the USDA–ARS Grain Marketing and Production Research Center (GMPRC) in Manhattan, Kansas. The elevator has a storage capacity of 1938 m³; it has one receiving pit and two bucket elevator legs. The dump pit in the receiving area measures approximately 366 × 366 cm and is covered by eight 45 × 360 cm steel bar grates. A dust control baffle system is located underneath the metal grates (Kenkel and Noyes, 1995). The baffle system is composed of two main components: fixed diagonal members, and pivoting vertical panels. As grain slides down through the diagonal members, the pivoting panels are pushed back, allowing the grain to enter the receiving hopper. When the grain flow stops, the pivoting members return to their vertical position, thereby sealing the opening and trapping the dust inside the pit. Two suction vents, which are part of the existing pneumatic dust collection system, are located inside the dump pit hopper. The dump pit hopper is 384 cm wide, 488 cm long, and 291 cm deep and can hold up to 28 m³ of grain. A belt conveyor transfers grain from the dump pit hopper to the bucket elevator leg at a rate of 12 kg/s.

The study was divided into four sets of experiments (table 1). The first two sets (experiments 1 and 2) were conducted without operating the pit conveyor and with the dust control baffles installed. For the last two sets of experiments (experiments 3 and 4), the pivoting panels of the dust control baffles were removed and the pit conveyor was operated to simulate conditions in actual grain elevator operation.

Table 1. Experimental design.

Experiment	Parameter Measured	Grain Flow Rate (kg/s)	Drop Height (cm)	Dust Control Baffle	Dump Pit Conveyor
1	Entrained air	114 87 47 17	53	Installed	Not operating
2	TSP emission	118 88 55 17	53	Installed	Not operating
3	TSP and PM10 emission	262 172 101 49	48 51 53 56	Removed	Operating
4	TSP and PM10 emission	260 173 103 50	38 41 43 46	Removed	Operating

EXPERIMENTAL SETUP AND TEST PROCEDURE
Air Entrainment

Air entrainment during grain receiving was measured using the apparatus shown in figure 1. Preliminary tests were conducted to develop a suitable experimental setup for air entrainment measurement. These tests involved dumping shelled corn through an opening in a plastic–covered dump pit with air exhausted through two holes in the plastic cover with 25 cm round exhaust ducts. The dust control suction vents were also sealed. As shown in figure 2, displaced and entrained air escaped through the spaces between the grain kernels as the grain spread out over the metal grate, leaving no obvious way to measure the entrained air. For those tests, mean airflow rate measured at the exhaust ducts (5.6 m³/min) were less than the volumetric grain flow rate (8.9 m³/min), indicating that a significant amount of air escaped through the grain as it spread.

To improve the airflow measurements from the dump pit, one of the metal grates was replaced with a 2 cm thick plywood sheet. The pivoting panels of the dust control baffle assembly directly underneath the measurement duct were also removed. A plastic sheet covered the dump pit perimeter and was sealed with duct tape. A wooden hopper (fig. 3) was placed on the center of the dump pit to avoid grain spillage and allow the grain to flow smoothly. Additional guide panels were placed on the hopper to prevent the escape of air at lower grain flow rates. Figure 3 shows the flow of grain as it passes from the slide gate to the wooden hopper. Unlike the grain flow with the metal grate in place, the grain flowed vertically through the slide gate and passed through the wooden hopper without the build up of grain. The major difference between the preliminary setup and the new setup is the effective drop height (h_e), which is the distance from the slide gate to the top of the grain build up (fig. 2). Because there was no build up of grain, the effective drop height without the metal grate is the same as the actual drop height. However, the removal of the grate should have minimal effect on air entrainment since the difference in drop height with and without the metal grate was small. In addition, minimal airflow can be induced by the grain during retarded flow with an almost flat slope, which is the case when the grain spreads on the grate.
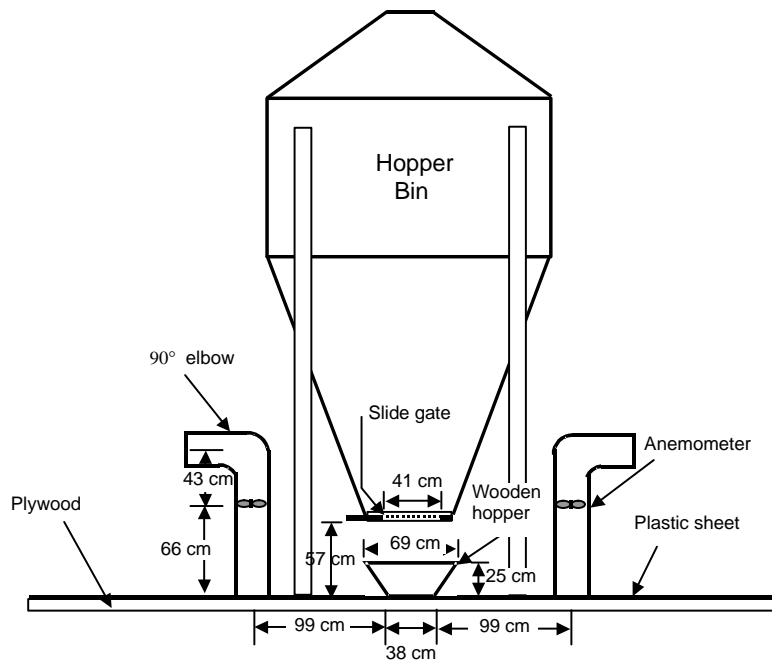
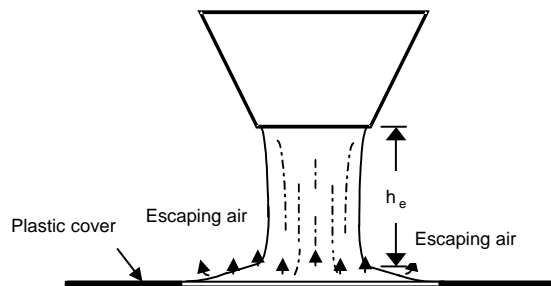**Figure 1. Schematic diagram of air entrainment setup (not to scale).**

Figure 2. Preliminary setup without the wooden hopper.

Two 22 cm diameter propeller anemometers (model 27106, R.M. Young Co., Traverse City, Mich.) were mounted in two 25 cm diameter round ducts to measure airflow rates induced by the falling grain. The propeller rotation generates DC voltage in a tachometer–generator, and this voltage is linearly related to air speed and airflow rate through the duct. A datalogger (21X Micrologger, Campbell Scientific, Inc., North Logan, Utah) recorded the voltage output from the anemometer. To establish the relationship between the volumetric airflow rate and voltage output, the anemometers were calibrated in a fan test chamber, which was designed and built according to AMCA standard 210–85 (AMCA, 1985).

A hopper–bottom truck was simulated by using a round steel hopper bin with a capacity of approximately 5 t of shelled corn (approximately 200 bushels). A slide gate at the bottom of the bin allowed variation in the grain flow rate. Four levels of grain flow rates were selected: 17, 47, 87, and 114 kg/s (table 1). Each grain flow rate test was replicated three times.

The design of the receiving pit, which was typical of pits in use in the grain industry, made it difficult to achieve a completely airtight system. To quantify air leakage through the system, the setup and operation of the system in figure 1 was modified. An axial–flow fan was installed on one side of the covered pit where one of the anemometers was originally located. One propeller anemometer was placed at the fan inlet
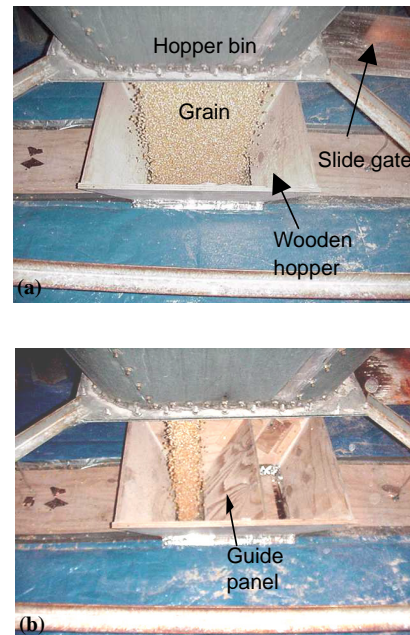

Figure 3. Grain flow through the wooden hopper at (a) full flow and (b) partial flow (1/4 slide gate opening).

to measure the inlet airflow rate. The other anemometer was positioned at the other side of the pit to measure exhaust airflow rate. Instead of dropping grain into the pit, the fan was operated to move air into the pit with airflow rates ranging from 1.8 to 14.9 m³/min. The leakage rate, which was the difference between the inlet and exhaust airflow rates, ranged from 1.1 to 4.0 m³/min. Regression analysis was used to estimate the leakage rate in subsequent tests in terms of the exhaust airflow rate.

All doors at the truck receiving area were closed to minimize the effect of ambient wind on airflow measurements. Corn was first loaded into the hopper bin from the overhead holding bin through a metal chute. The volume of

corn was estimated by taking the product of the cross–sectional area of the storage bin (6.9 m^2) and the difference between initial height and final height of the grain level in the bin. The corn was unloaded by opening the hopper bin slide gate for a predetermined time (0.6 to 4.0 min). The average grain mass flow rate (m_g) was computed as:

$$m_g = V\rho_b / t \qquad (1)$$

Additional 90° elbows were connected to the airflow measurement ducts above the anemometers (fig. 1) to prevent the air leaking through the doors from influencing airflow measurements. These elbows should have had negligible effect on the measurements since they were located upstream of the anemometers. Volumetric airflow rates coming out of the ducts were determined from voltage readings by the datalogger at 0.5 s intervals during each test. Air temperature and relative humidity were measured during each test with an aspirated psychrometer, and atmospheric pressure was determined using a mercury barometer. Static pressure under the plastic enclosure was also measured for each grain flow rate with an inclined manometer. Static pressure ranged from

2.5 to 7.5 Pa, indicating that the enclosure had minimal restraint on the flow of air through the ducts.

The amount of entrained air was expressed in terms of specific air entrainment, SA (m^3 of air/m^3 of grain), and was computed based on the mass balance:

$$SA = (Q_{exh} + Q_{leak} - Q_{grain}) / Q_{grain} \qquad (2)$$

TSP Emission (Small Hopper Bin)

For TSP emission rate measurement, the receiving pit perimeter was enclosed using plywood and plastic sheeting (fig. 4). The enclosure, with a vertical cross–sectional area of 1.9 m^2 (354 cm wide × 53 cm high), served as a channel for dust–laden air. All the doors in the truck dump pit area were closed during the test. In order to simulate and control the effect of ambient wind, four box–type fans, located on one end of the enclosure, were operated to blow air across the 366 × 366 cm pit area at speeds ranging from 47 to 54 m/min. Three high–volume (HiVol) samplers with 20 × 25 cm glass–fiber filters (type A/E, Pall Life Sciences, Ann Arbor, Mich.) were placed on the other end of the enclosure to collect TSP samples
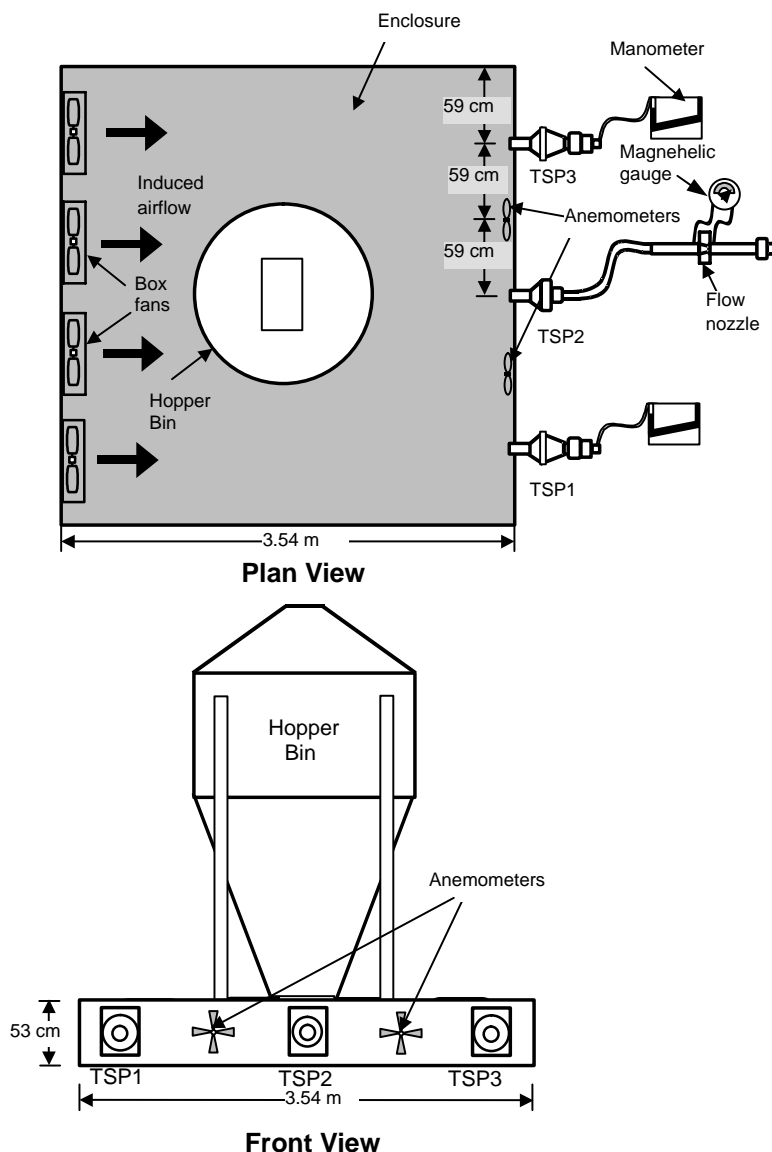

Figure 4. Schematic diagram showing the setup for TSP emission measurement using a 5 t hopper bin (not to scale).

under isokinetic conditions. The sampling flow rates of TSP samplers 1 and 3 (model 500, Bendix Corp., Lewisburg, W.V.), which had 10 × 20 cm sampling probes, were determined from pressure drop measured by an inclined manometer at the sampler exhaust. The sampling flow rate for TSP sampler 2, which had a 6 × 20 cm probe, was measured by a calibrated flow nozzle and a magnehelic pressure gauge. Two propeller anemometers were mounted between the HiVol samplers to measure the air speed coming out of the enclosure.

The same hopper bin and similar slide gate openings used in air entrainment measurement (experiment 1) were used for TSP emission measurement. The corresponding grain flow rates and test conditions are shown in table 1 (experiment 2). There were also three replicates of each grain flow rate for experiment 2.

Preliminary receiving tests were conducted to estimate the average air speeds across the enclosure while grain was being dumped. The mean air speed was 50 m/min, ranging from 47 to 54 m/min. This air speed was used to establish the isokinetic sampling flow rates for the HiVol samplers.

The dust collection filters were weighed in an electronic balance (Mettler Instrument Corp., Highstown, N.J.) with an accuracy of ±0.001 g and were carefully placed in the filter holders. The filters were conditioned 24 h before and after sampling in a room kept at a temperature of 22°C and relative humidity of 25%. The sampling flow rates were adjusted with variable voltage transformers to attain the isokinetic sampling condition. The box fans and the samplers were turned on approximately 10 s before unloading the corn to allow the desired sampling flow rate to be reached and were turned off after all the unloaded corn was inside the dump pit. The sampling period started when the corn was unloaded and terminated when the samplers were turned off.

The total mass of shelled corn used in each test was determined by taking the product of the corn volume and its bulk density (771 kg/m^3). Voltage signals from the anemometers were recorded at 0.5 s intervals by the datalogger and converted to air speed using the calibration equation. The volumetric flow rate through the enclosure was estimated by taking the product of the enclosure cross−sectional area and the average air speed.

Concentrations of TSP were computed by dividing the mass of TSP collected by the total air sampling volume. Total air sampling volume is the product of the volumetric sampling flow rate and the sampling time. The TSP emission rate (TSP$_{ER}$) was expressed as the mass of dust per mass of grain:

$$\text{TSP}_{ER} = (C_{TSP}Q_a t_s) / (M) \qquad (3)$$

TSP and PM10 Emission (Large Hopper Bin)

The 5 t hopper bin could only provide a grain flow rate of up to 118 kg/s, which was lower than the actual grain flow rates of hopper−bottom trucks. To achieve higher grain flow rates and different drop heights, the small hopper bin was replaced with a larger bin with a capacity of 8 t of corn. The experimental setup for the 8 t hopper bin (fig. 5) was similar to that for the 5 t hopper bin (fig. 4) with some modifications, as described below.

In order to measure both TSP and PM10 emissions, the enclosure cross−sectional area was increased from 1.9 to 3.0 m^2 (354 cm wide × 85 cm high) to accommodate two TSP samplers and two PM10 sampling inlets (model 1200, ThermoAndersen, Smyrna, Ga.). The two PM10 samplers

were positioned horizontally alongside two TSP HiVol samplers. The sampling flow rates of the two TSP samplers were adjusted with variable voltage transformers and by changing the sampling probe size. Sampling for PM10 was conducted at a constant flow rate of 1.1 m^3/min. The sampling flow rates were indicated by the pressure drop measured by an inclined manometer and magnehelic gauges at the sampler exhaust. Samples of TSP and PM10 were collected on 20 × 25 cm glass−fiber filters. Four box−type fans were operated on the other end of the enclosure to simulate a unidirectional ambient wind of approximately 38 m/min. The receiving pit conveyor was operated during the test at a rate of approximately 12 kg/s to simulate actual grain elevator operation.

Grain flow rate was adjusted using a drop gate at the bottom of the bin. With such adjustment of the drop gate, there was also a change in drop height of about 2.5 cm per change in grain flow rate. The drop height from the drop gate to the dump pit metal grate was further modified by lowering the legs of the hopper bin by 10 cm to attain two sets of drop heights for the different grain flow rates. Four drop gate openings, corresponding to four grain flow rates, were considered. Two sets of experiments (experiments 3 and 4) were conducted based on the grain flow rate and drop height combination as shown in table 1. Each grain flow rate/drop height treatment was replicated three times.

Preliminary receiving tests were conducted to measure the average air speeds across the enclosure using the propeller anemometer. Initial tests indicated that the large cross−sectional area of grain flow through the drop gate blocked the airflow induced by the box fans near the center of the enclosure. A wooden board was placed in the center of the enclosure to divert the dust and airflow to the sides of the enclosure opening and minimize the blocking effect of the grain flow. Air speed measurements were taken at two points on each of the two open sides of the enclosure. The air speed ranged from 28 to 54 m/min with a mean of 38 m/min. This air speed was used to establish the isokinetic sampling flow rates for the TSP HiVol samplers and estimate the airflow rate through the enclosure. The same corn unloading and air sampling procedure used in the 5 t capacity bin was employed. The volumetric flow rate through the enclosure was estimated by taking the product of the open area on the two sides of enclosure and the average air speed on that area. The TSP$_{ER}$ value was then calculated in terms of the mass of TSP per mass of grain using equation 3. Similarly, PM10 emission rate (PM10$_{ER}$) was computed as the mass of PM10 per mass of grain:

$$\text{PM10}_{ER} = (C_{PM10}Q_a t_s) / (M) \qquad (4)$$

CORN SAMPLING AND ANALYSIS

Three 27 t corn lots were used in the study. Two different corn lots were used for experiments 1 and 2, while another corn lot was used for experiments 3 and 4. Samples were collected from the elevator leg as the grain was transferred back to the storage bin through a diverter−type mechanical sampler (Carter−Day Co., Minneapolis, Minn.). Moisture content was measured using an automatic grain moisture tester (Motomco model 919, Seedburo Co., Chicago, Ill.). Bulk density was determined using a grain scale (model 8800A, Seedburo Co., Chicago, Ill.). Broken corn kernels and foreign materials (BCFM) content was analyzed with a Carter−Day dockage tester. After three test runs, the samples collected in the
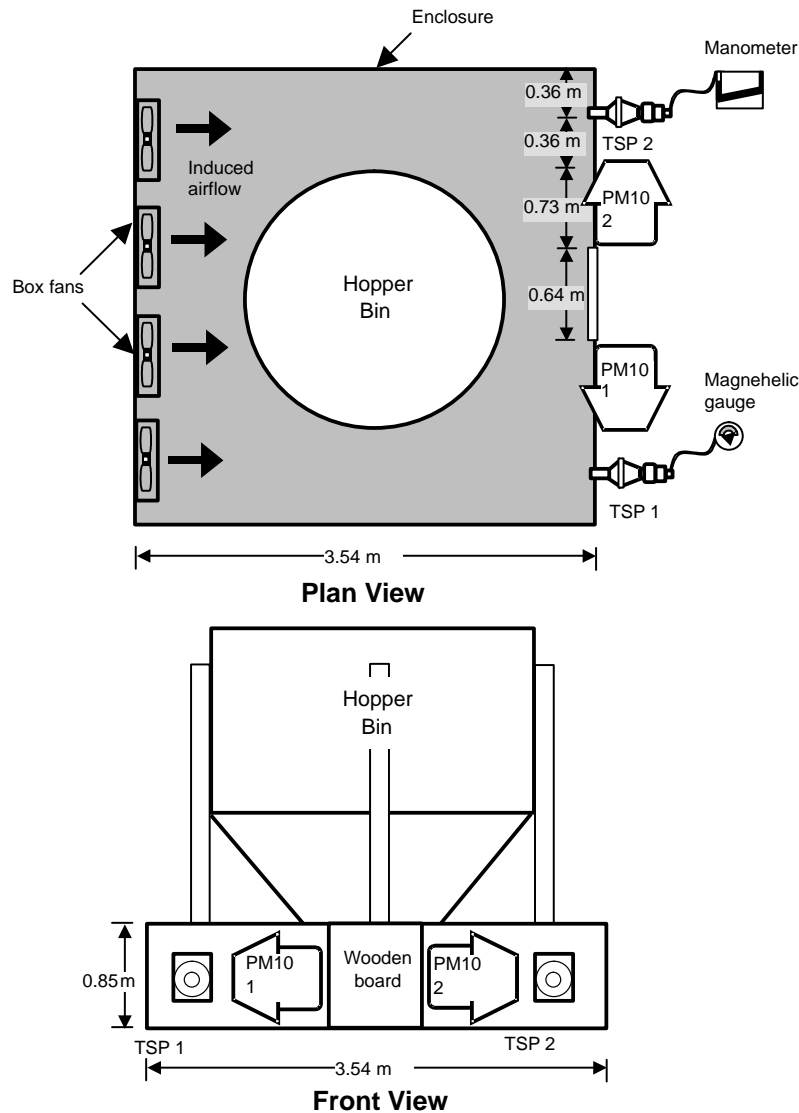
Figure 5. Schematic diagram showing the setup for TSP and PM10 emission measurement on the 10.5 m³ (8 t of corn) hopper bin (not to scale).

Table 2. Mean physical properties of corn samples obtained from the elevator leg.[a]

Experiment	Moisture Content, % wet basis (SD)	Bulk density, kg/m³ (SD)	BCFM, % (SD)
1	11.5 (0.06)	767 (1.2)	18.1 (1.3)
2	14.1 (0.02)	771 (2.1)	3.3 (0.2)
3	13.4 (0.16)	761 (2.0)	2.0 (1.4)
4	13.4 (0.15)	750 (4.5)	3.4 (0.9)

[a] Values represent means of three replicates; values in parentheses represent standard deviations.

mechanical sampler were subdivided into three 1 kg subsamples and were analyzed (table 2).

ANALYSIS OF DATA

The effect of grain flow rate on SA and TSP emission rate measured with 5 t hopper bin (experiments 1 and 2) was determined using the General Linear Model (GLM) procedure in PC–SAS (SAS Institute, Inc., Cary, N.C.). Comparisons of mean differences were performed using the Least Square Means (LSMeans) option of the GLM procedure. Linear and non–linear regression analyses were performed using all data points (not just the mean values for each grain flow rate) to describe the relationship between grain flow rate and the parameters measured. For experiments 3 and 4, the GLM procedure was also used to determine the effects of grain flow rate and drop height on TSP and PM10 emissions rates. An interaction term between grain flow rate and drop height was included in the model. Again, all data points were used in the analysis. Significance of mean differences of TSP and PM10 emission rates at different drop heights was analyzed using a t–test. A 5% level of significance was used.

RESULTS AND DISCUSSION

AIR ENTRAINMENT

Mean values of SA (and ranges) were 0.26 (0.16 to 0.36), 0.42 (0.37 to 0.51), 0.94 (0.72 to 1.08), and 2.07 (2.04 to 2.13) m³/m³ for grain flow rates of 114, 87, 47, and 17 kg/s, respectively. Comparison of the means indicated that higher grain flow rates had significantly ($p < 0.05$) lower specific air entrainment, although the grain flow rates of 114 and 87 kg/s did not differ significantly ($p > 0.05$) in SA. This observation was similar to that observed for powders and other granular
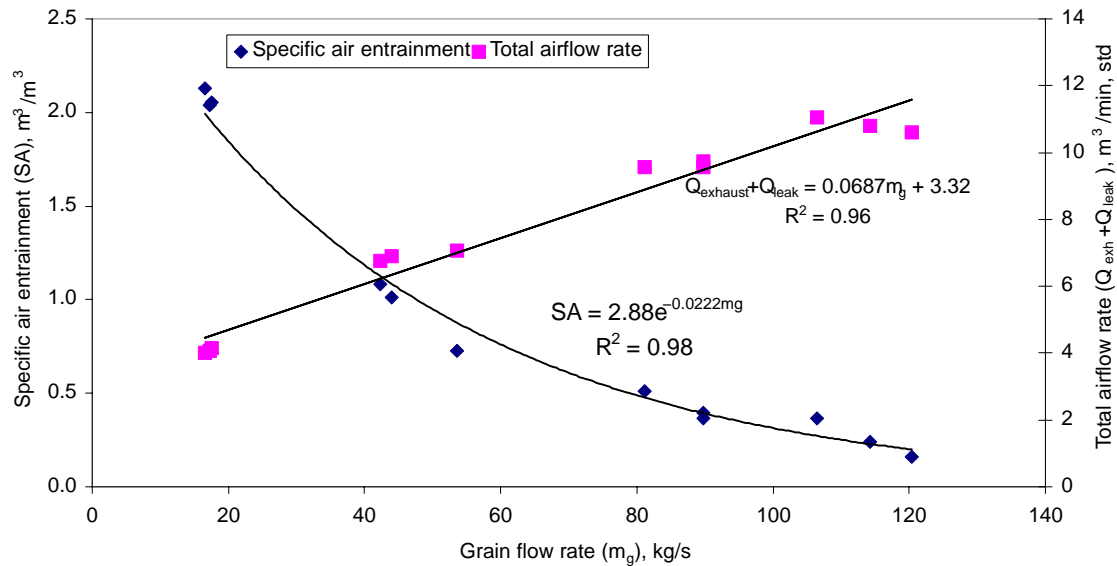
Figure 6. Specific air entrainment (SA) and total airflow rate (Q_{exh} + Q_{leak}) at grain flow rates of 17 to 118 kg/s (standard temperature = 20°C; standard pressure = 101.3 kPa). All data points are used in the regression analysis.

materials (Plinke et al., 1991; Cooper and Arnold, 1995). Regression analysis on all the data points indicated that the relationship between SA and grain flow rate can be described with an exponential model:

$$SA = 2.88e^{-0.0222\,mg}; R^2 = 0.98 \qquad (5)$$

Mean values (and ranges) of the total volumetric airflow rate (Q_{exh} + Q_{leak}) were 10.8 (10.6 to 11.1), 9.6 (9.6 to 9.7), 6.9 (6.8 to 7.1), and 4.1 (4.0 to 4.1) m³/min for grain flow rates of 114, 87, 47, and 17 kg/s, respectively. The mean (Q_{exh} + Q_{leak}) increased significantly (p < 0.05) with increasing grain flow rate. This was primarily due to the increase in the amount of displaced air associated with the increased grain flow rate. Figure 6 shows that a linear model can be used to describe the relationship between total volumetric airflow rate and grain flow rate:

$$(Q_{exh} + Q_{leak}) = 0.0687\,m_g + 3.32; R^2 = 0.96 \qquad (6)$$

TSP EMISSION

TSP emission rates for the 5 t hopper bin were measured with the dust control baffles installed and the pit conveyor not operating. For the 8 t hopper bin, TSP and PM10 emission rates were measured with the baffle pivoting panels removed and the pit conveyor operating.

Small Hopper Bin

For the 5 t hopper bin, the mean values (and ranges) of TSP$_{ER}$ were 8.3 (8.1 to 8.4), 9.0 (8.7 to 9.3), 12.0 (11.1 to 12.5), and 14.6 (13.7 to 15.8) g/t for grain flow rates of 118, 88, 55, and 17 kg/s, respectively. The TSP$_{ER}$ values for the different grain flow rates were significantly different (p < 0.05), except for the higher flow rates (88 and 118 kg/s), which did not differ significantly (p > 0.05). Similar to SA, TSP$_{ER}$ decreased with increasing grain flow rate (fig. 7):

$$TSP_{ER} = -0.0634\,m_g + 15.4; R^2 = 0.88 \qquad (7)$$

The above mean TSP$_{ER}$ values were within the range of published values for hopper–bottom truck receiving: 8.5 g/t at a 75 kg/s corn flow rate (Shaw et al., 1998), 9.5 g/t for wheat (Kenkel and Noyes, 1995), and 16 g/t (Midwest Research

Institute, 1998). The measured TSP$_{ER}$ values were slightly lower than the EPA (1998) emission factor for corn receiving with hopper–bottom trucks of 17.5 g/t, possibly because of the reduction in dust emission by the dust control baffle in the present study.

The dust emission levels during bulk receiving were affected by two main factors: the wind currents in the receiving area, and dust generated by the falling grain stream when it strikes the receiving pit (Wallace, 2000). In this study, variability due to wind currents was minimized by using a controlled wind source (i.e., box fans) and closing the doors of the receiving area. Differences in dust emission, therefore, were mainly due to the displacement of air from the pit and entrainment of air by the falling grain. Increase in the mass of dust emitted per mass of material due to relative increase in volume of entrained air per mass of material was also observed for granular solids (Plinke et al., 1991). The higher emission rates measured at lower grain flow rates were expected due to the higher specific air entrainment. In addition, corn falling at high flow rates tended to spread radially outward on the metal grates, resulting in the slow decrease in the velocity of the falling particles at the center of the grain build up. A similar behavior has been reported for cement and sand. This flow behavior resulted in smaller impaction and separation forces, generating less dust (Plinke et al., 1991).

Large Hopper Bin

The TSP emission rates measured using the 8 t hopper bin and with the pit conveyor operating are summarized in table 3. In general, TSP$_{ER}$ decreased with increasing grain flow rate and decreasing drop height. The mean TSP$_{ER}$ ranged from 11.8 g/t at a grain flow rate of 173 kg/s and drop height of 41 cm to 52.1 g/t at a grain flow rate of 49 kg/s and drop height of 56 cm. From the GLM model, the TSP emission rate was related to grain flow rate (m_g, kg/s) and drop height (h, cm) by the following model:

$$TSP_{ER} = -137 + 0.495\,m_g + 3.42\,h - 0.0109\,m_g h \qquad (8)$$

$$R^2 = 0.93$$

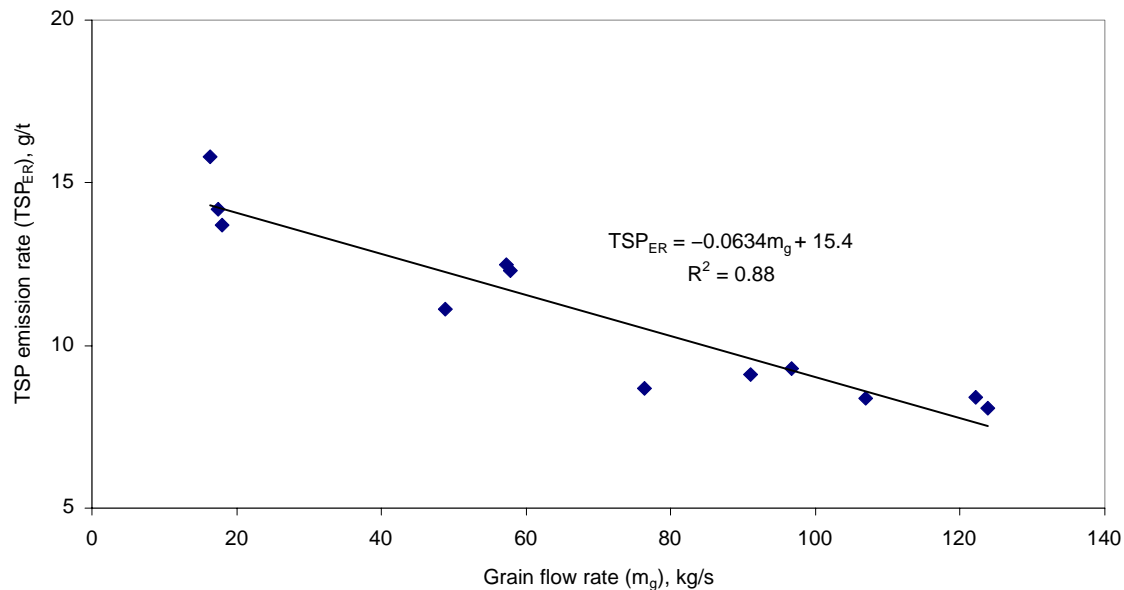The mean TSP emission at 41 cm drop height (11.8 g/t),

Figure 7. TSP emission rates (TSP$_{ER}$) at grain flow rates of 17 to 118 kg/s and drop height of 53 cm. The receiving pit was equipped with a dust control baffle, and the pit conveyor was not operating. All data points are used in the regression analysis.

Table 3. TSP and PM10 emission rates measured at different grain flow rates and drop heights with the pit conveyor operating.

Drop Gate Opening	Grain Flow Rate (kg/s)	Drop Height (cm)	TSP$_{ER}$ (g/t)[a]		PM10$_{ER}$ (g/t)[a]	
			Mean	Range	Mean	Range
1	262	48	21.5 a	18.6–25.8	1.8 a	1.2–2.4
	260	38	12.1 b	9.1–12.5	0.6 b	0.5–0.8
2	172	51	25.9 a	24.8–27.4	2.8 a	2.0–3.7
	173	41	11.8 b	11.0–14.3	0.7 b	0.6–0.8
3	101	53	30.0 a	26.9–32.3	2.8 a	2.0–3.7
	103	43	14.3 b	11.6–16.6	1.2 b	0.6–2.0
4	49	56	52.1 a	51.1–52.2	6.1 a	5.2–6.7
	50	46	18.6 b	15.7–22.0	1.1 b	0.8–1.7

[a] Means within the same drop gate opening (grain flow rate) followed by the same letter are not significantly different (p > 0.05).

which was the drop height measured for actual hopper trucks, was within the range of published values: 8.5 g/t (Shaw et al., 1998) to 16 g/t (Midwest Research Institute, 1998). Similar to the TSP$_{ER}$ result with the 5 t hopper bin, the decreasing trend in TSP emission rate with increasing grain flow rate could be attributed to the decreasing amount of entrained air and reduced impaction and separation forces due to reduced falling particle velocity. The increase in drop height resulted in a relative increase in potential energy of grain before falling and an increase in kinetic energy as the material hit the pile. This increase in total energy due to the higher drop heights increased impaction, causing more dust to be generated (Plinke et al., 1991; Plinke et al., 1995). Thus, higher values of TSP$_{ER}$ were observed at larger drop heights (48 to 56 cm) than at smaller drop heights (38 to 46 cm). Martin (1985) reported a similar trend in corn dust emission concentration in a laboratory drop test. Another possible reason for the increase in TSP emission rates with increasing drop height was the increase in the amount of entrained air. Studies with granular materials showed that increasing drop height caused an increase in the amount of entrained air per amount of material, which in turn increased the amount of dust generated (Plinke et al., 1991; Cooper and Arnold, 1995).

PM10 EMISSION

The PM10 emission rates measured using the 8 t hopper bin and with the pit conveyor operating are summarized in table 3. Similar to TSP$_{ER}$, PM10$_{ER}$ decreased with increasing grain flow rate and increasing drop height. The highest mean PM10$_{ER}$ was 6.1 g/t at a grain flow rate of 49 kg/s and a drop height of 56 cm, while the lowest was 0.6 g/t at a grain flow rate of 260 kg/s and a drop height of 38 cm. The percentage of PM10 relative to the TSP emitted varied between 5.0% and 11.8%. From the GLM model, PM10$_{ER}$ was expressed as a function of grain flow rate and drop height:

$$PM10_{ER} = -19.6 + 0.0663 \, m_g + 0.460 \, h - 0.00145 \, m_g h \quad (9)$$

$$R^2 = 0.85$$

At lower drop heights, the grain had a lower falling velocity before impact, causing smaller impaction forces and producing less fine particulates. The proportion of PM10 measured in this study was relatively lower than data published by EPA (1998) of 20% to 30%. The results were closer to the fraction of PM10 measured by Shaw et al. (1998) at 13.6% (SD = 2.79) using a Coulter Counter Multisizer. However, their result provided a conservative estimate for PM10 percentage. Coulter Counter analysis usually overestimates the amount of smaller particles due to the breakup of agglomerates during sample preparation (Treaftis et al., 1987; Shaw et al., 1998). Therefore, the actual percentage of PM10 present in TSP was expected to be even lower than that measured by the Coulter Counter method.

CONCLUSIONS

This research measured the rates of entrained air, TSP emission, and PM10 emission during shelled corn receiving as affected by grain flow rate and drop height. The following conclusions were drawn:

- The specific air entrainment increased from 0.27 to 2.07 m³/m³ as grain flow rate decreased from 114 to 17 kg/s.

- Total volumetric airflow rate coming out of the receiving pit increased linearly with grain flow rate.
- For grain flow rates of 17 to 118 kg/s with dust control baffles, the dump pit conveyor not operating, and a drop height of 53 cm, TSP emission rates increased linearly from 8.3 to 14.6 g/t of grain with decreasing grain flow rate. Without the dust control baffles and dump pit conveyor operating, TSP emission rates also decreased from 52.1 to 11.8 g/t as grain flow rate increased from 49 to 262 kg/s.
- PM10 emission rates increased with decreasing grain flow rate and ranged from 0.6 to 6.1 g/t of corn. The PM10 emission rates were between 5.0% and 11.8% of TSP emission rates.
- Both TSP and PM10 emission rates increased with increasing drop height.

The results presented in this article suggest that considerable amount of air is entrained by the falling grain and that considerable amounts of particulate matter (TSP and PM10) are emitted during the receiving process. Such entrained air and emitted particulate matter should be considered in designing and/or operating dust control systems. Additionally, the results suggest that the grain flow rate and drop height are important parameters that could be used to control air entrainment and dust emission. Dumping at higher grain flow rates would reduce emissions of particulate matter.

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NOMENCLATURE

C_{PM10}	Average PM10 concentration (g/m^3)
C_{TSP}	Average TSP concentration collected by the HiVol samplers (g/m^3)
h	Drop height (cm)
h_e	Effective drop height (cm)
M	Total mass of corn received (t)
m_g	Grain mass flow rate (kg/s)
PM10	Particulate matter less than 10 μm in aerodynamic diameter
$PM10_{ER}$	PM10 emission rate (g/t)
Q_a	Average volumetric flow rate through the enclosure (m^3/min)
Q_{exh}	Average volumetric airflow rate from the ducts (m^3/min)
Q_{grain}	Total volumetric grain flow rate (m^3/min), or bulk volume of corn (V) divided by the unloading time (t). The outflow of the grain from the pit was zero because the dump pit conveyor was not operating during the entrained air tests.
Q_{leak}	Estimated air leakage rate (m^3/min)
ρ_b	Bulk density of corn (kg/m^3)
SA	Specific air entrainment (m^3/m^3)
t	Unloading time (min)
t_s	Sampling time (min)
TSP	Total suspended particulates
TSP_{ER}	TSP emission rate (g/t)
V	Bulk volume of corn (corn kernels and void space) received (m^3)